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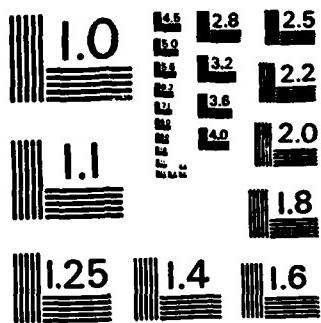
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**Final Report on the
Creation of a Closed Field Line Compact
Toroid System By Counterstreaming Rotating
Relativistic Electron Beams**

J.D. SETHIAN, K.A. GERBER, AND A.E. ROBSON

Plasma Physics Division

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September 30, 1982



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FINAL REPORT ON THE CREATION OF A CLOSED FIELD LINE COMPACT TOROID SYSTEM BY COUNTERSTREAMING ROTATING RELATIVISTIC ELECTRON BEAMS

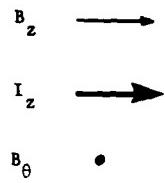
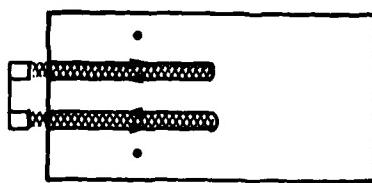
I. INTRODUCTION

Many varied and significantly different methods of creating a Compact Toroid are being vigorously pursued, each spurred onward by the promise of a plasma containment configuration that sports many inherent advantages over more conventional toroidal confinement schemes: the absence of magnetic coils linking the center hole, the attainment of relatively high β plasmas, and the opportunity for an utterly simple first wall, have combined to make Compact Toroids, after only a few short years of research, one of the most respected contenders in the Advanced Fusion Concepts community. Unfortunately, the very simplicity of the Compact Toroid makes it difficult to set up, and the various approaches being tried (plasma guns, spheromak, reversed field theta pinch) all suffer from their own peculiar disadvantages.

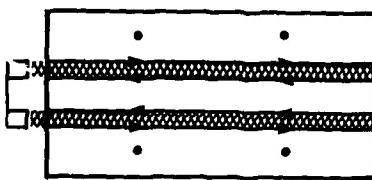
The objective of this program was to produce a Compact Toroid by a novel method using two rotating relativistic electron beams. The beams are sequentially injected into neutral hydrogen gas contained in a closed metal tube. By adjusting the gas pressure so the plasma created by the first beam is sufficient to neutralize the beam charge, but not the beam current, the first beam can be made to induce the poloidal and toroidal fields, heat the plasma, and upon leaving the system, induce persistent plasma currents that maintain these fields (See Fig. 1). These fields consist of a reversed B_z (poloidal) field and an external B_θ (toroidal) field, the latter being maintained by a continuous net axial current that returns through the tube walls. After passage of the first beam, the second beam is injected between the first beam-created plasma and the wall, and from the opposite end of the system. The sense of rotation of this beam is such that the initial poloidal fields are amplified, and the current is adjusted so that the toroidal field outside of the first beam is just cancelled, leaving no net axial current. The toroidal field is now contained solely in the plasma. A small amount of diffusion at the system ends, plus the natural tendency for the plasma to pull away from the walls and contract axially, produces the desired configuration. This process is shown schematically in Fig. 1. The tendency to contract is expected, not only because it is energetically favorable, but because the beginnings of such a contraction have been observed during the decay of the single beam-produced open current line configuration, as in stage c of Fig. 1 (see Ref. 1).

The primary advantage in producing a Compact Toroid in this manner is the relative simplicity with which it is formed: as the beams produce both the field and plasma, no applied magnetic field or plasma source is required. All of the electrical components are contained in the electron beam generators, and as theirs is a well-established technology, developed for DoD as well as DoE applications, no state-of-the-art or esoteric devices are required. Furthermore, the vacuum vessel and first wall can be made quite simple, or more importantly, can be readily configured to accept whatever post formation heating scheme, if any, is deemed necessary. In particular, this method readily lends itself to heating by adiabatic compression, either by an imploding liquid metal liner as in the NRL LINUS concept,² or a conventional theta pinch coil.

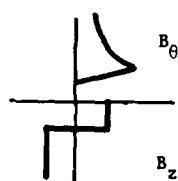
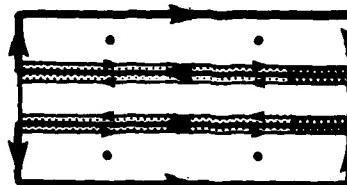
A. BEAM 1 BREAKS DOWN GAS, FORMS THE MAGNETIC FIELDS



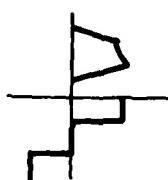
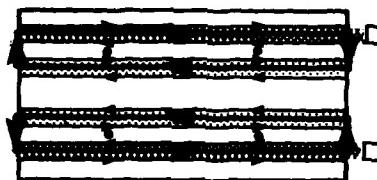
B. BEAM HEATS PLASMA



C. BEAM 1 EXITS, INDUCES PLASMA CURRENTS TO MAINTAIN REVERSED B_z AND NET AXIAL CURRENT (I_z)



D. BEAM 2 GENERATES A SECOND CONFIGURATION, CANCELLING NET I_z AND ELIMINATING B_θ OUTSIDE PLASMA



E. CURRENT AND FIELD LINES CLOSE AROUND PLASMA, PRODUCING COMPACT TOROID

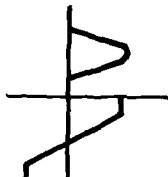
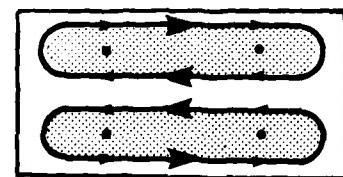


Fig. 1 — Formation of a Compact Toroid with Electron Beams

II. HISTORICAL BACKGROUND

In the first significant steps towards producing a Compact Toroid in this manner, it was demonstrated¹ that a single rotating beam can generate a reversed field plasma with a toroidal field in an initially field free metal tube (i.e. stage c of Fig. 1). Magnetic fields with persistence times of up to 20 μ sec and plasmas with electron densities of $2 \times 10^{16} \text{ cm}^{-3}$ and temperatures of 7 eV were achieved.

After it was ascertained that the current lines were not closed inside the plasma, but rather returned through the tube wall, an extensive experimental study of the mechanism by which the beam forms the magnetic fields was carried out. This study resulted in the derivation and verification of a simple model,³ in which the beam radius and pitch angle is determined by conservation of canonical angular momentum, conservation of flux, and magnetic force balance; and the beam velocity is determined by the balance of power between the capabilities of the diode and the requirements of the induced fields.

As a result of that study, it then became possible to predict the propagation of the second beam in the presence of the plasma and fields produced by the first. Among the conclusions drawn from this model were: (1) a first beam current pitch angle of $\alpha_1 = \arctan v_\theta/v_z \sim 55^\circ$ is optimal, as this ensures the second beam will be well away from both the plasma and the wall (v_θ and v_z are the net azimuthal and axial velocities of the beam, respectively); (2) the current pitch angle of the second beam, $\alpha_2 = 45^\circ$; (3) the axial flux enclosed by each beam i.e., that enclosed by the cathode emission surfaces, must be the same; and (4) the energy required of the second beam to close the current lines is less than half that required of the first beam to form the initial configuration. This model is described in the Appendix.

As will be discussed in this report, experiments with two electron beams demonstrated the basic scientific validity of this concept. We injected a second counterstreaming rotating beam that completely neutralized the axial current left by the first, and produced an amplified, longer-lived poloidal field. However the propagation of this second beam was greatly hindered by plasma external to the first beam channel. This plasma, as we found out, is inherent to the propagation of a rotating beam, and, in the current experiments restricted the parameter range in which axial current cancellation could be achieved. This, in turn, prevented the attainment of a satisfactory plasma containment system. Thus, it was not deemed worthwhile, from a CTR standpoint, to pursue this program further.

In the pages that follow, we present a detailed account of the two beam program. A narrative format was chosen, not only for its readability, but also because it provides an excellent vehicle for conveying the many diverse problems and corresponding solutions that we encountered. We hope the reader will be instructed, enlightened, and, entertained.

III. THE EXPERIMENTAL INVESTIGATION

Attempt I

The first electron beam was provided by TRITON (700 kV, 60 kA, 120 nsec), the workhorse used for all the single beam studies. The second beam was provided by the more powerful POSEIDON (1 MeV, 100 kA, 120 nsec) which was built expressly for this task. (POSEIDON is described in detail in a forthcoming NRL Memorandum Report.⁴) One of the primary concerns was precise timing between the two beams, and considerable effort was spent in achieving a very low jitter in the generators. In POSEIDON, the jitter in Marx erection was less than ± 9 nsec, and the total jitter of the entire generator was less than ± 60 nsec, the latter figure reflecting the breakdown characteristics of the water switch used in the Blumlein. In any event, this figure was more than adequate considering the 20 μ sec persistence time of the configurations. After bringing POSEIDON on line, the techniques that were developed to achieve low jitter were applied to TRITON, resulting in a jitter of ± 70 nsec (the difference between the two accelerators was attributable to variations in the Marx column design).

The experimental facility is shown in Fig. 2. This consisted of an interaction chamber and vacuum system that could readily be moved to allow access to the front end of the generators. A remote control gas fill system allowed precise adjustment of the fill pressure. Each rotating beam was produced, at first, by means of a "half cusp." In this arrangement a flat pancake coil was placed between the anode foil and an aluminum plate. When the coil was energized, the field lines emanated perpendicular to the cathode emission surface and, because they could not penetrate the aluminum plate during the coil current pulse length, were diverted radially outward immediately after the foil. The interaction of the axially directed beam with the radially directed field caused the beam to rotate.

The most complex components of the system were the two foil changers, which allowed the anode foils, which rupture on every shot, to be replaced without breaking the system vacuum. Basically complex airlocks, these items were essential to the experiment, as it would be otherwise impossible to evacuate both the generator diodes and interaction chamber with the foils in place. Moreover, the foil changers were versatile enough to handle anode foils of different materials and to allow treatment of these foils prior to each shot. (For example, it was anticipated that a TRITON beam dump would have to be placed in the center of POSEIDON's foil.) In addition, these changers also: (1) housed the cusp field coils, (2) contained the flux excluding plate that formed the cusp, and (3) made a readily broken mechanical and electrical link between the diodes and the interaction chamber. A photograph of the experimental facility appears in Fig. 3.

This investigation had to be carried out on a trial and error basis. As entirely new ground was being covered (evidenced in this document by a lack of references to anybody else's work except our own), the most logical course for us to follow was to start with an arrangement based on the one beam experiment, and observe what happened.

Following this logic, we set up POSEIDON exactly as TRITON, with a single titanium anode foil. The only difference was that POSEIDON used a 5.0 cm radius cathode, whereas TRITON used a 3.8 cm radius one. TRITON's applied flux and current were set to give a beam pitch angle of 55° and a radius of 3.8 cm. (See Fig. A-2). Then, in accordance with the two beam model, POSEIDON's applied flux and current were adjusted to be equal and 50% larger than those of TRITON, respectively. The primary diagnostics throughout this investigation were a battery of magnetic probes set to measure B_z and B_θ just inside the chamber wall at five equally spaced axial positions. After ensuring that we could easily generate a single ended configuration with either TRITON or POSEIDON, we tried them together, with POSEIDON firing 2 μ sec after TRITON (an artist's conception of the expected signals is shown in Fig. 4).

This first set of experiments was quite uneventful. TRITON fired fine, but POSEIDON's diode completely shorted. It became immediately clear that the cause of this was that TRITON's beam penetrated the POSEIDON foil and formed a plasma in the diode. But then we allowed for this contingency when we spent \$40,000 on foil changers. Needless to say, there was no evidence of POSEIDON's beam on the magnetic probes downstream.

Attempt II

Our first attempt at keeping TRITON out of POSEIDON was to place a second titanium foil, separated by a 3 mm gap, on the drift tube side of POSEIDON's foil. We knew from previous experience³ with a vacuum Faraday cup that a rotating beam cannot readily penetrate a thin titanium foil, due to image currents generated in that foil by the self-fields at the beam head. However, in practice, some particles, on the order of 10%, do manage to get through. It was thought that a second foil would stop all these strays.

Nature did not agree with our reasoning, and we still observed a shorted diode.

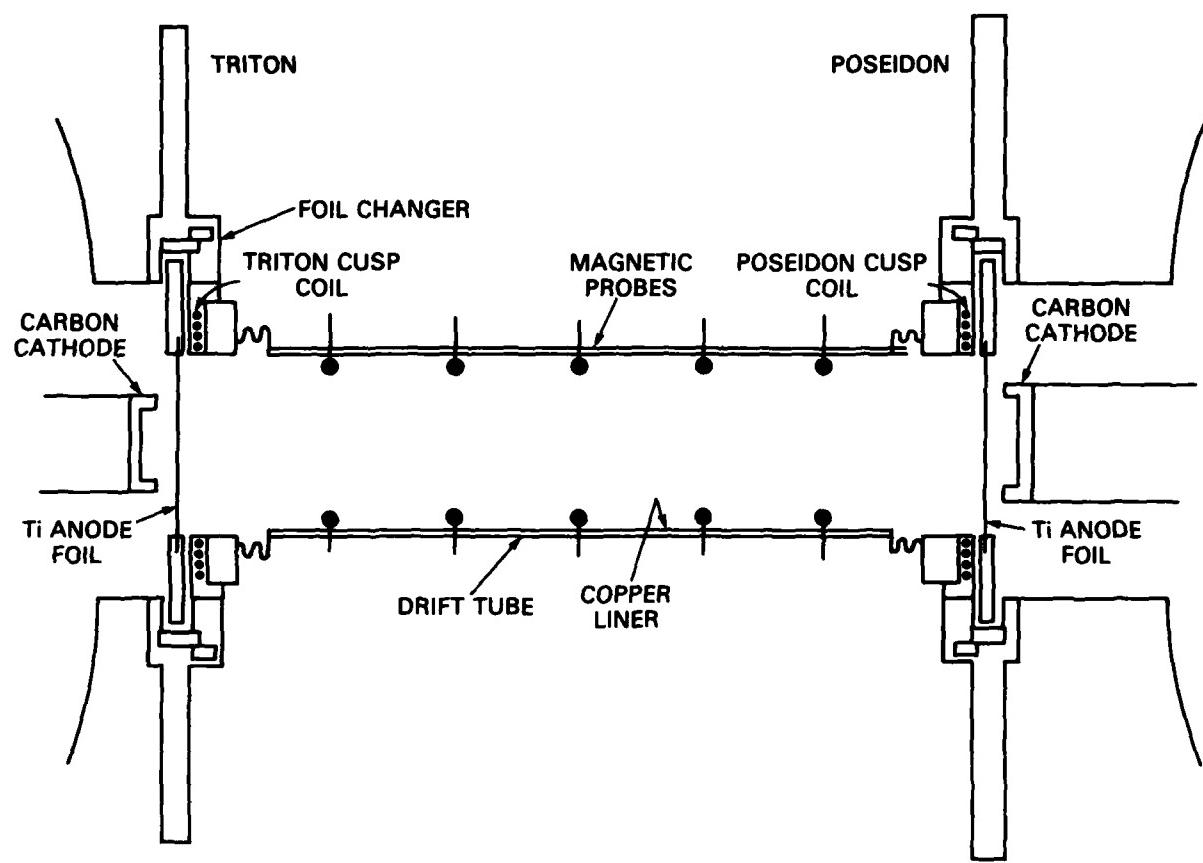


Fig. 2 — The Experimental Facility

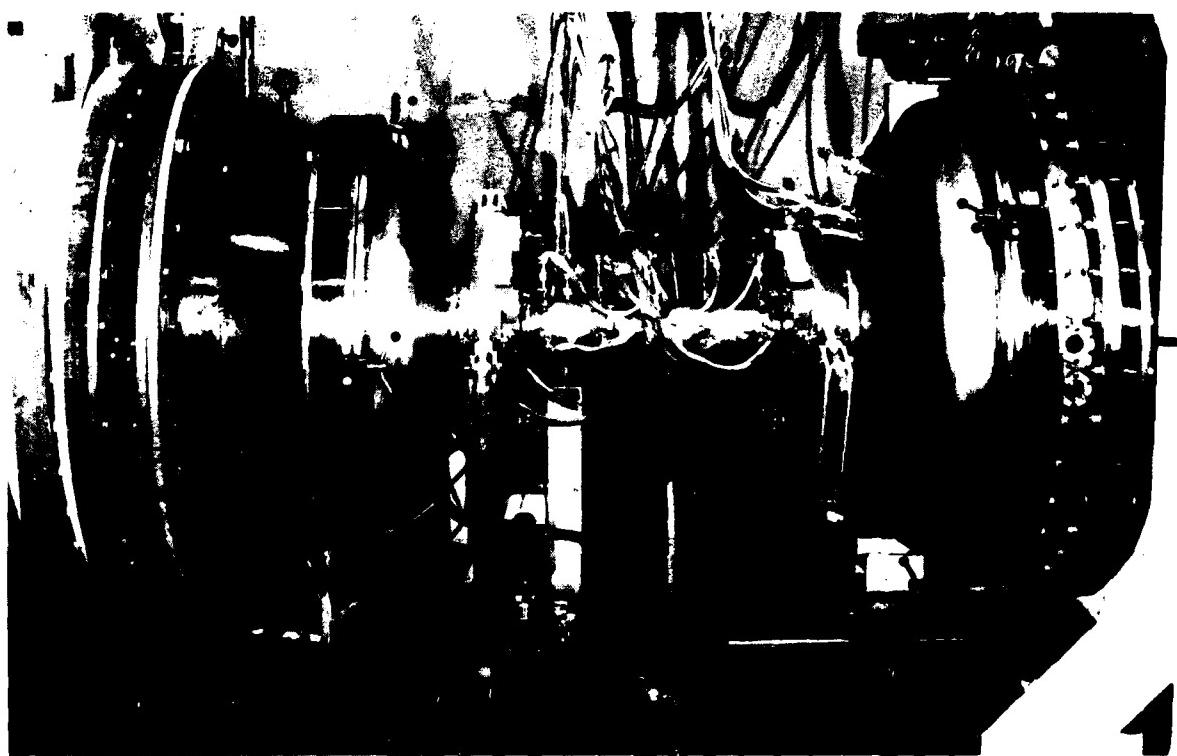


Fig. 3 — Photograph of the Experimental Facility. POSEIDON is on the right.

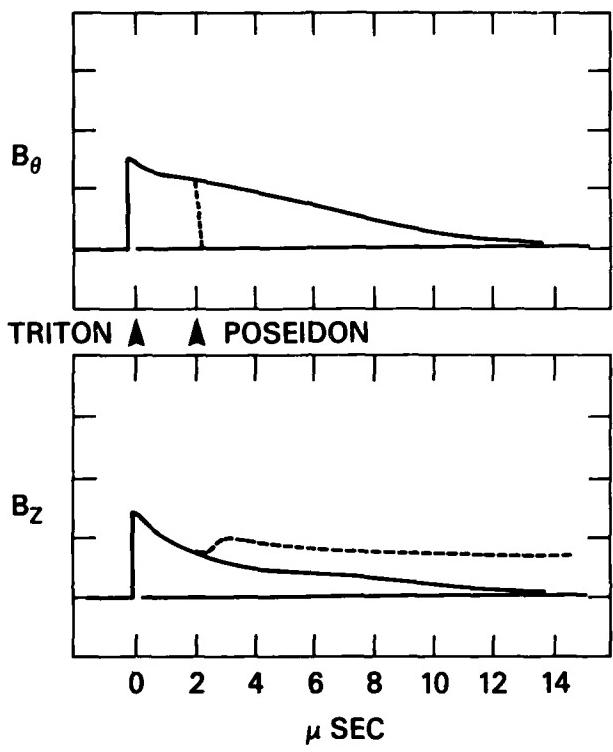


Fig. 4 — Artist's conception of data from probes measuring B_θ and B_z just inside the drift tube wall. The solid line indicates the effect of TRITON only, the dotted line the effect of firing POSEIDON as well. Arrows mark injection time of the two beams. The presence of B_z (reversed Poloidal field) in the absence of B_θ (i.e. no net axial current) signifies a compact toroid has been produced.

Attempt III

The next thing to do was obvious: a 3 mm thick aluminum disc was placed in the center of POSEIDON's foil, on the drift tube side. The radius was chosen to be 3.8 cm, large enough to block TRITON's beam, but small enough to allow POSEIDON's beam to pass. With this arrangement POSEIDON's diode became operational, albeit at a lower impedance than if it were operated alone. Thus even though TRITON's electrons were still getting into the diode, they were not in sufficient quantities to prove fatal.

Of greater interest were the probe signals downstream. The B_θ probes showed very small (<10%), very short lived (<50 nsec) drops in the axial current, in the anticipated direction at the anticipated time. What was not anticipated, however, was that the B_z probes also showed a drop, as if POSEIDON's beam was rotating the wrong way. After the gales of laughter subsided, our first impulse was to accuse the technical crew for reversing the electrical connections to one of the cusp coils. Finally convinced of their innocence, we sought a more esoteric explanation... and soon found one. The self-field of TRITON's beam was reconnecting with the cusp field of POSEIDON in such a manner as to invert the radial field through which POSEIDON was injected. (See Fig. 5). This inverted field then did indeed rotate POSEIDON's beam the "wrong" way. Score: Nature, three; Physicists, nothing.

Attempt IV

It was decided that if TRITON's self-field insisted on connecting with POSEIDON's cusp field, it should do so in a constructive, rather than detrimental, fashion. To do this necessitated putting a coil inside POSEIDON's cathode, complete with an internal copper flux excluder to propagate a region of zero flux between the two beams. (See Fig. 6.) Whilst the technical details of this coil are outside the scope of this report, and would break the story line anyway, the reader is urged to admire at his leisure the technical wizardry which led to the successful installation of an externally powered 10 kG field coil inside a cathode which floats up to over one million volts; and not produce any ground loops. Figure 7 may prove useful for such an exercise.

The experiment was tried out, and lo and behold, no propagation was observed downstream. In fact it now proved difficult to generate a configuration with POSEIDON alone: The probe signals were down by a factor of two and extensive damage from deviant electrons was observed inside the diode. The reasons for this was that in order for this internal coil to work TRITON's self field *must* reconnect with the field of this coil, and the aluminum disc on POSEIDON's foil was preventing this.

Attempt V

Lucite was the obvious candidate for a disc material, although also the messiest from a vacuum cleanliness standpoint. Again no propagation was observed. However, we did observe considerable damage on the diode (POSEIDON) side of the lucite disc, indicating the beam was pinching. We came up with four explanations: (1) The field lines were not reconnecting in their intended manner, (2) Because POSEIDON's beam was not injected along an axial magnetic field, there was no force to keep a non-rotating beam (i.e. in the diode) from pinching under the influence of its own self B_θ field, (3) Because of the geometry, POSEIDON's beam particles experienced a radial field before attaining their full energy, and hence could be turned around before traversing the foil. (This is the principle behind a magnetically insulated diode.) and (4) The equilibrium radius of POSEIDON's beam was grossly different when it was free streaming as opposed to when it was propagating outside of TRITON's beam: In the former case the equilibrium radius was less than TRITON's, in the latter case, greater. (This is because both TRITON and POSEIDON had the same axial flux, but POSEIDON's current was larger (see Fig. 8).) Thus if the POSEIDON beam started rotating before getting to the TRITON beam, it would have had an opportunity to pinch to a smaller radius.

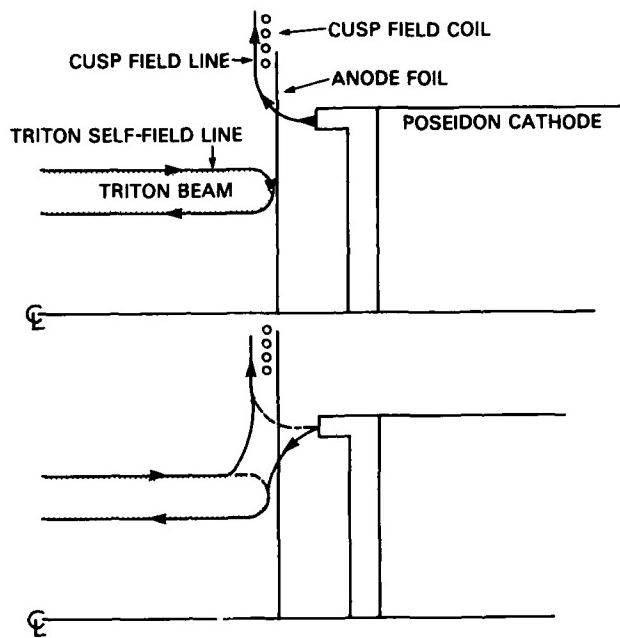


Fig. 5 — Conceptual drawing of TRITON's self-magnetic field reconnecting with POSEIDON's cusp field. Note that before reconnection, the radial field through which POSEIDON is injected is directed outward, whereas afterwards it is directed inward, thus causing POSEIDON's beam to rotate in the wrong sense.

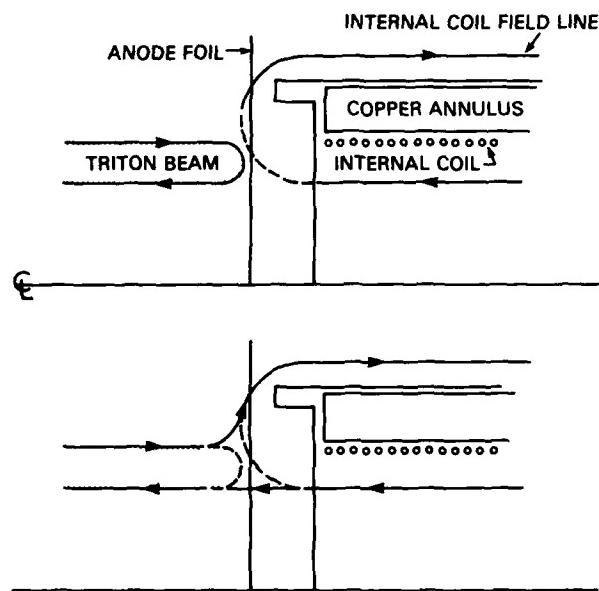


Fig. 6 — Conceptual drawing of the Internal Coil. Here reconnection with TRITON's self-field does not reverse the radial field of POSEIDON.

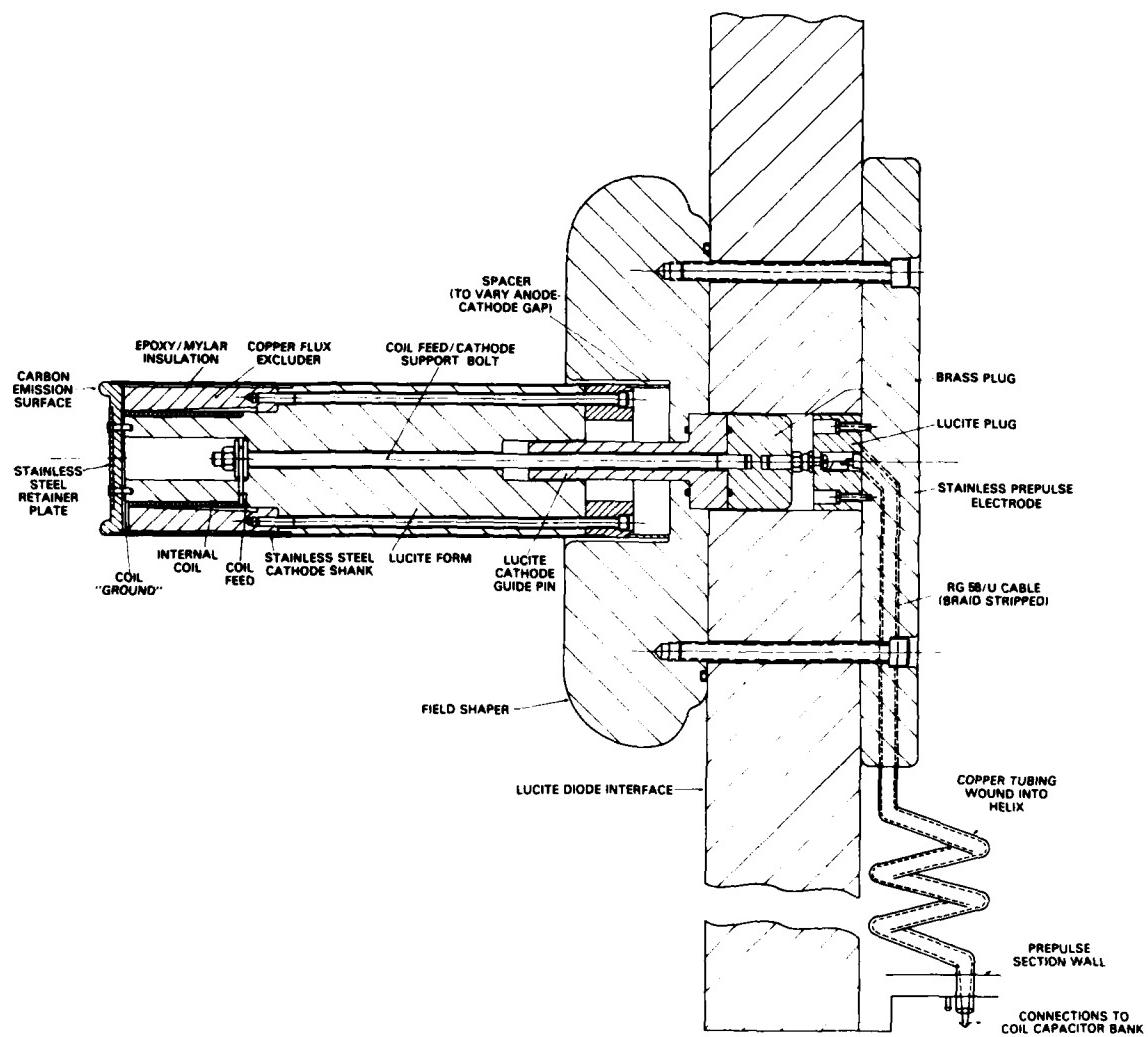


Fig. 7 — Machine Drawing of the Internal Coil. Coil was powered by a 3 kV, 450 Joule capacitor bank. Copper annulus is slit in order to prevent formation of azimuthal eddy currents.

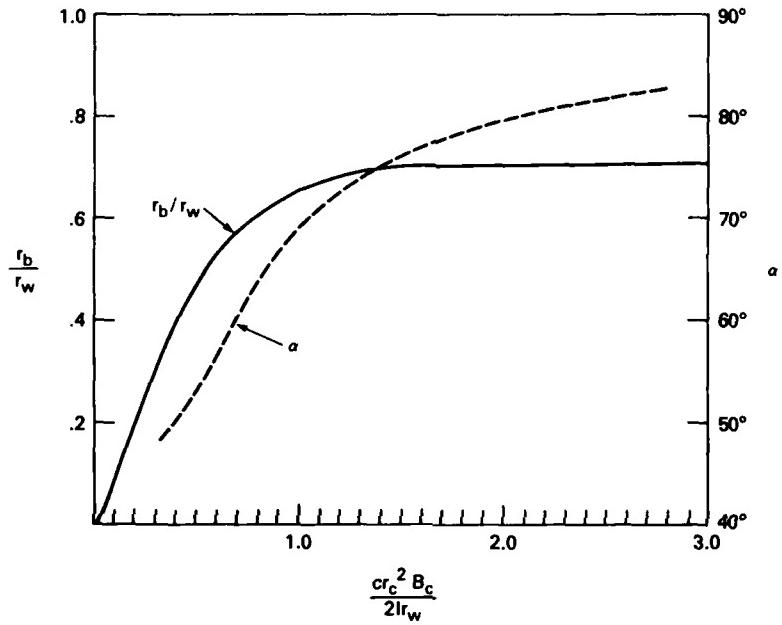


Fig. 8 — Electron beam radius r_b , and pitch angle α , as a function of cathode radius (r_c), cusp axial field (B_c), beam current (I), and the tube wall radius (r_w). From Ref. 3.

Attempt VI

As the possibilities for failure were overwhelming, and only one of them, number 3, could be eliminated through calculation, it was decided to eliminate some of the others through independent study. Several magnetic probes were installed to measure the behavior of the TRITON beam's self-fields in the vicinity of POSEIDON's foil. It was found that at drift tube fill pressures of $150 \mu\text{H}_2$ or less, the axial current was not continuous all the way to the foil. From TRITON's foil to about 2 cm from POSEIDON's foil (a distance of 58 cm) the axial current was constant within $\pm 15\%$. However, within 2 cm of the foil this current dropped off dramatically, and at .5 cm from the foil, the current had dropped to 20% of its original value. This implied that the TRITON configuration was not uniform up to the POSEIDON foil, and explained why other measurements showed the axial flux on the POSEIDON side of the foil was down by 80% of its value in the drift tube center. This did not bode well for the constructive reconnection camp.

The situation improved dramatically at fill pressures exceeding 200μ . The B_θ probes showed a uniform distribution within at least .5 cm from the foil (the closest we could get), and the axial flux in the POSEIDON diode at .1 cm from the foil was within 20% of that at drift tube center. However the axial flux dropped off rapidly with distance from the foil, and at 1 cm from the foil (the cathode position), had dropped to 25% of the original value. This is to be expected, for the same reason that axial flux falls off with distance away from any solenoid.

The penetration time of the flux through the titanium foil was observed to be 500 nsec. This is in contrast to a desk top experiment in which the penetration time was measured directly and found to be 300 nsec. Presumably the difference is due to the presence of a plasma on the foil surface. [Incidentally, the penetration time of a whole host of materials was measured, the fastest being aluminized mylar which clocked in at 50 nsec. Experience had shown, however, that this material was considered *persona non grata* as an anode for two reasons: (1) It tended to let a lot of TRITON's beam into POSEIDON's diode, and (2) It tended to be obliterated on each shot. This allowed the lucite disc to fall, according to trajectories defined by Newton and Murphy, into such a position as to thoroughly disable the foil changer.]

The conclusion drawn from these experiments was that to realize a controlled reconnection it would be necessary to push the radial field lines of the internal coil as far outward as possible, and preferably past the foil. This would eliminate all but possibility Number 2. We would also have to operate at higher fill pressures than normal, but this would cause no special problem.

Attempt VII

Moving the field lines outward was accomplished by placing an aluminum collar outside the cathode. As shown in Fig. 9, this collar forced all the field lines to return on a larger radius, and thus effectively increased the annular thickness of the solenoid.

While measurements did show the radial field lines were pushed outward, performing the two beam experiment still gave the same unspectacular results: No observation of POSEIDON's beam downstream, and damage on the backside of the diode. It now became apparent that possibility Number 2 was a reality—the beam was pinching in the diode. In fact, experiments in which POSEIDON's beam was injected into a lucite plate located at the anode plane showed a final radius of about 4.0 cm, or only .2 cm larger than the lucite disc. It was not looking good for the home team.

Attempt VIII

In a text-book application of the if-you-can't-beat-'em-join-'em school, it was decided to let the beam pinch, but let it start off at a larger radius than before, so its final radius would still be larger than

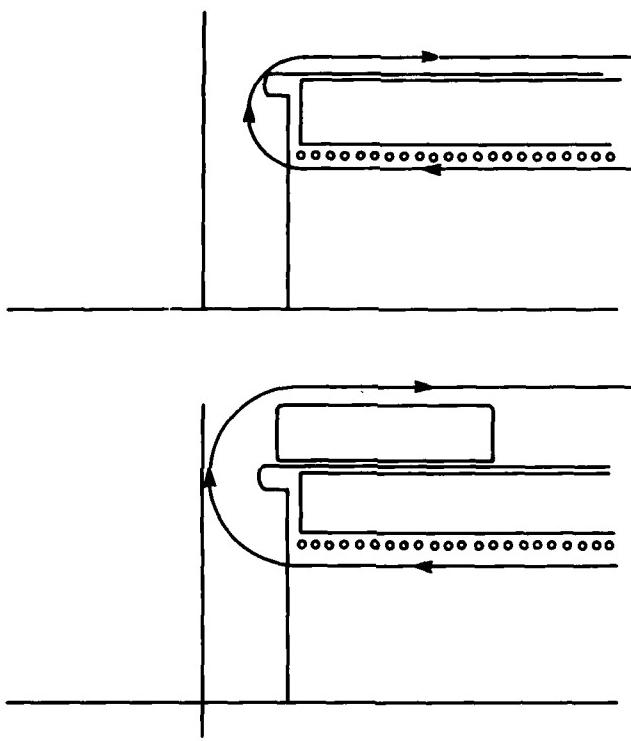


Fig. 9 — Effects of the aluminum collar. The collar is split in the same manner as the copper annulus.

TRITON's beam. (Fig. 10). POSEIDON did not readily accept having the cathode diameter increased from 5.0 cm to 6.3 cm, and put up quite a protest, with radial emission, shorted diodes and self-destructing cathodes. Most of the problem was due to the external collar, which was now separated from the diode wall by only twice the anode-cathode gap. Nevertheless, the generator eventually accepted this latest mutation, most of the electrons were convinced to go through the foil in a harmonious manner, and the experiment was tried.

Much to the amazement of all concerned, we observed long lived dips in the B_θ signals (some as much as 25%), corresponding rises in the B_z signals, and temporary decreases in the B_z decay rate. The changes were small, but reproducible. A representative trace is shown in Fig. 11. After months of seeing no evidence whatsoever of POSEIDON's beam, these results were welcome indeed. Moreover, as they arrived just hours before a critical 6.1 sponsor review, one of us (AER) was moved to quote Samuel Johnson: "Depend on it, sir, when a man is to be hanged in the morning, it concentrates his mind wonderfully."

Attempt IX

When the self-applause abated to a mild din, we attempted to optimize the configuration by embarking on a journey into parameter space. We varied everything: POSEIDON/TRITON flux and current ratios, POSEIDON anode cathode gap, tube fill pressure, POSEIDON/TRITON timing, time of the day, etc. While we met with some successes, we were still unable to achieve total cancellation of the net current. This was attributed to three reasons: (1) despite all our attempts, we were never able to inject more than 50% of the total diode current downstream with the internal coil, (2) what current was injected was so close to TRITON's beam, that any plasma just outside the main channel could readily current neutralize POSEIDON's beam, and (3) as the beam started to rotate, its self-field brought about an unpinching force, which in turn resulted in a very thick annular cross section inhomogeneous beam, at least compared to normal cusp injection. (This was verified with witness plates.)

Attempt X

Convinced of the futility of trying to fight all the injection problems inherent with the internal coil, we repeated the cusp coil experiments with the larger radius cathode. This would, in principle, (1) result in an unpinched, well defined homogeneous beam that (2) would be at a large enough radius to not detrimentally reconnect with TRITON's self field. We turned out to be only half right, and observed an unpinched, well defined homogeneous beam rotating the wrong way.

Attempt XI

Fighting the sinking lost-in-the-woods-and-running-around-in-circles feeling, we decided to take time off and study exactly what was happening at POSEIDON's foil. To do this, we replaced POSEIDON with a lucite drift tube section, complete with its own titanium foil. This section was evacuated and thus would appear to TRITON's beam much like POSEIDON's diode. See Fig. 12. A formidable battery of diagnostics were brought to bear on this section: streak and framing camera, Langmuir probes (including a somewhat exotic double probe designed to detect 7eV plasma electrons, but be impervious to the 700 keV beam electrons), several x-ray detectors, open shutter cameras, an array of thermocouples, magnetic field probes, Rogowski coils, voltage probes and photomultiplier tubes.

The observations from these experiments were most interesting. High energy electrons were entering the mock diode region in sufficient quantity to light up 10μ of air. Total current flowing through the region was 700 Amps. Different size masks placed on the foil indicated they were uniformly distributed in radius, and thus implied they were not confined by the annular reversed field configuration. In fact, their time of arrival, as indicated by the onset of light from this region, was approximately 20 nsec after TRITON's current started (indicating a velocity $.14 c \leq v \leq c$) and a full

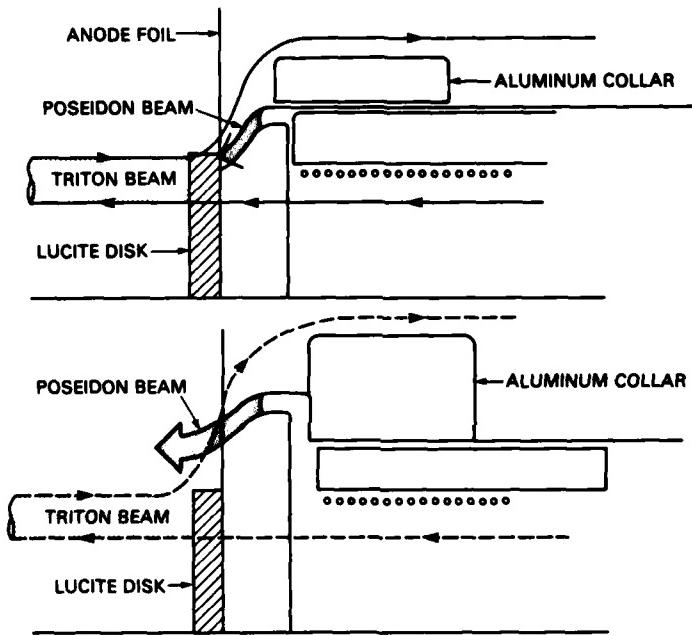


Fig. 10 — Conceptualized effect of increasing cathode radius

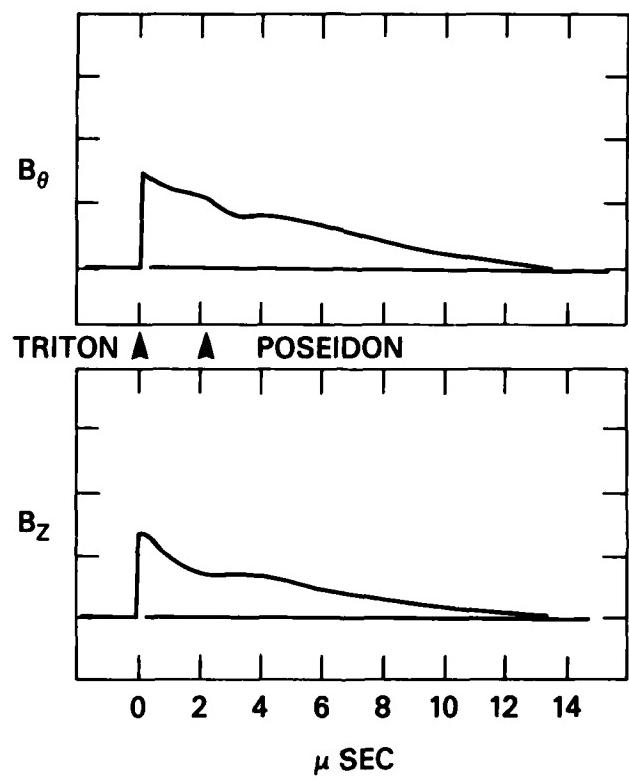


Fig. 11 — First indication of POSEIDON beam propagating downstream. Axial position is 10 cm from POSEIDON diode.

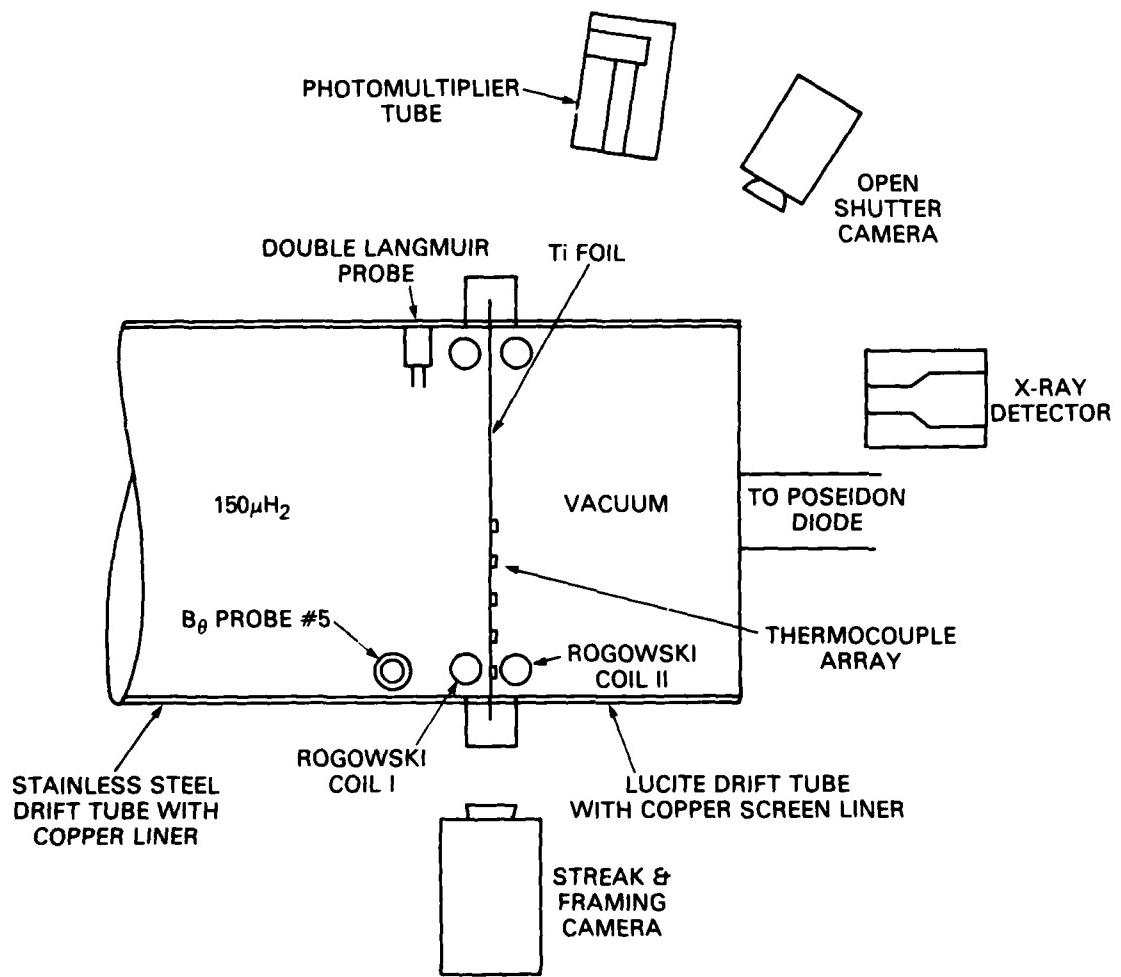


Fig. 12 — Experimental configuration to study beam propagation past POSEIDON foil

60 nsec before the main beam front arrived (with velocity $v \sim .044 c$). These results are presented in Fig. 13. The energy of these precursor electrons, as determined by using different anode foils, was at least 150 keV. (A double foil, as tried in Attempt II, did not prevent the electrons from penetrating this region). Throughout these studies, a clean, well defined 3.8 cm radius, 1 cm thick annular pattern was observed on the main drift tube side of the foil, indicating TRITON's configuration was behaving as predicted. An annular pattern was verified semi-quantitatively with an array of thermocouples: those located at radii 0, 1, 2, 5, and 6 cm showed no signal, those at radii of 3 and 4 cm blew out the oscilloscope channels they were connected to.

The light itself was peaked at a wavelength between 3200 Å and 4000 Å and endured for some 60 nsec. Both of these observations indicated that we were looking at N_2 recombination ($\lambda \sim 3361 \text{ \AA}$, radiative lifetime at $10\mu \sim 60 \text{ nsec}$). The light intensity increased over the range of $1 - 10\mu$. (We do not normally operate at such a high pressure in the diode; rather the 10μ of N_2 was used simply for diagnostic purposes).

A number of auxiliary tests were performed to verify the source of this light: 3 mm thick lucite discs placed over the entire TRITON foil and/or over the POSEIDON duplicate diode foil ensured the light was not due to x-rays produced in the diode, in the drift tube, or electrons produced in the POSEIDON foil by inverse Compton scattering. A mask with an annular opening placed over TRITON's foil ensured these electrons did not originate from outside the main emission region. (This was very doubtful to begin with, as only those electrons generated on axis could possibly, without the benefit of the main beam self-field, escape the cusp field). Finally, the remote possibility of some sort of microwave or electrical breakdown was eliminated.

The source of these precursor electrons was postulated as follows: When the beam is injected into the tube, it represents a sudden presence of negative charge. An electric field is then set up, with the field lines extending from the beam head to the drift tube wall, and in some cases, even all the way to the POSEIDON foil. Electron beams are known to be accompanied by copious amounts of ultraviolet radiation and x-rays. This radiation produces electron-ion pairs well ahead of the beam front (i.e. outside the influence of the self-magnetic field). The ions are accelerated along these field lines, into the beam, and their relatively large Larmor orbit allows them to penetrate the self field. The electrons, on the other hand, are accelerated away from the beam and, while some smash harmlessly into the tube wall, others penetrate POSEIDON's foil.

The problems caused by this with respect to the two beam experiment were: (1) POSEIDON's cathode could become charged (although experimentally we were unable to measure this effect with POSEIDON's voltage monitor), (2) POSEIDON's diode was filled with plasma, even if the main part of TRITON's beam was blocked off (This explained the relatively low impedance of POSEIDON when fired after TRITON) and (3) the entire drift tube was filled with plasma, making propagation of POSEIDON difficult. This last fact proved, in the end, to be the major obstacle in this experiment.

Attempt XII

Given the above conditions, it became clear that a new approach was needed. Brilliant Idea Number 12 was to insert a 3.8 cm radius, 10 cm long aluminum cylinder in front of POSEIDON's foil. The philosophy here was to thoroughly decouple the three phases of POSEIDON's beam: generation in the diode, rotation in the cusp and introduction to the TRITON formed plasma: (1) With a normal cusp field, POSEIDON's beam was born in a straight axial field and did not pinch, (2) The cusp field lines were diverted radially outward one third of the way down the length of the cylinder, ensuring the beam was rotating well before being injected around the TRITON produced configuration, (3) Since the cylinder was conducting and at the same radius as the TRITON configuration, the POSEIDON beam would not be able to distinguish between the two and could easily make the transition. In addition, as this device presented a considerable protuberance on the anode foil, the electric field lines emanating from the beam front would terminate on it, and the precursor electrons would be kept out of the diode.

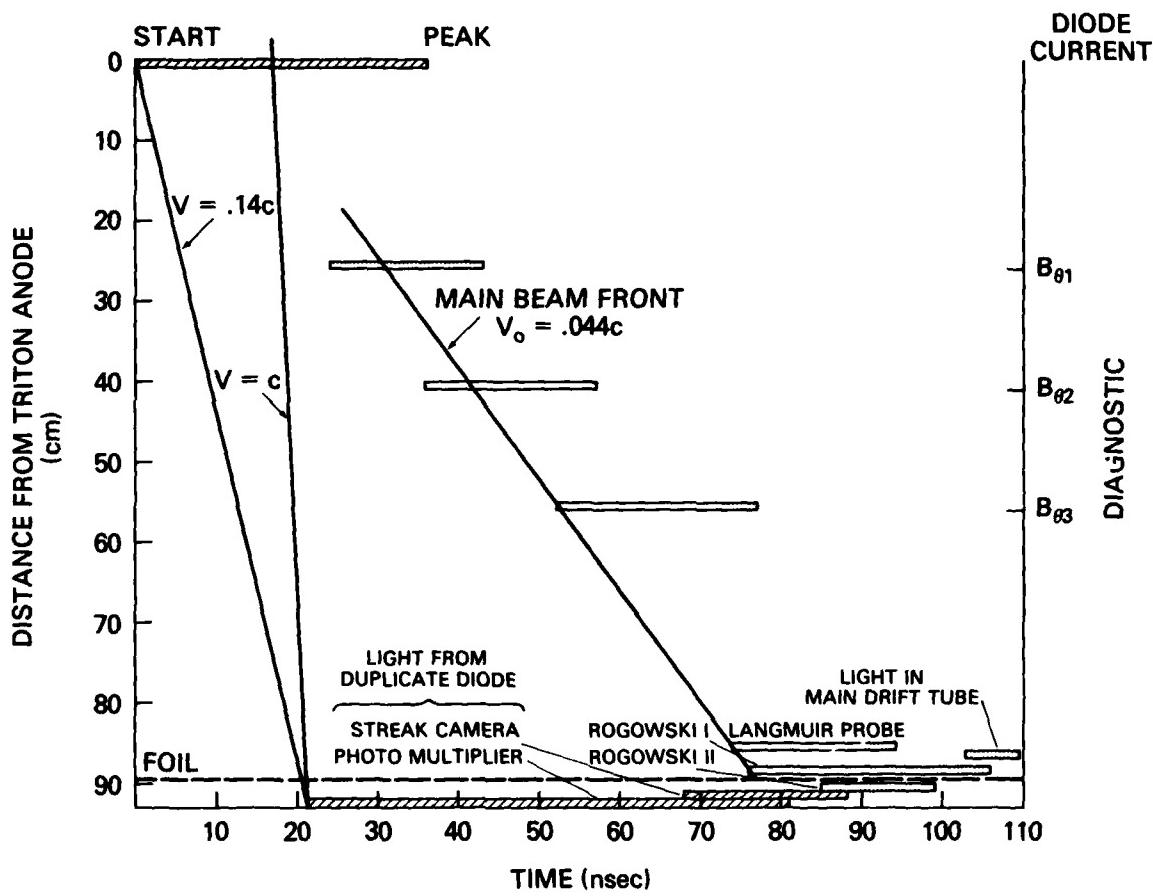


Fig. 13 — Results of set up for Fig. 12. The y axis is calibrated in cm from TRITON's diode, with position of each diagnostic indicated on right side. The x axis is calibrated in nsec. All signals are fixed from a common fiducial generator. The width of all magnetic signals corresponds to 10% to 90% points in signal rise. While the main beam front propagates with velocity $v \sim .044c$, in accordance with the beam propagation model³, the light from the mock diode region turns on before the beam front arrives (Note that the streak camera is not as sensitive to 3361\AA , the observed N_2 line, as the PM tube, and consequently only responds to the brightest portion of the glow.)

The installation of this device in such a manner as to guarantee contact with POSEIDON's foil (no arcing could be afforded, lest a plasma be formed in the region where POSEIDON's beam was starting to rotate), to minimize the perturbation on POSEIDON's beam, and to survive same was yet another technical *tour de force*. To guarantee that TRITON's beam was not repelled from this object by self-induced image currents, and that the electric field was indeed enhanced, several 3 mm diameter roll pins were inserted into the front end of the cylinder. This device, shown in Fig. 14, was soon after dubbed the "meat tenderizer" after it was inadvertently placed, roll pins up, on a control room chair.

To summarize the results, we got it half right. For the first time POSEIDON's diode exhibited virtually no change in impedance whether or not TRITON fired first. Moreover, when TRITON alone was fired, the observation of a normal B_θ signal but no B_z signal at a position halfway along the length of the meat tenderizer indicated that TRITON's beam was being completely absorbed, as intended. However, with still no propagation of POSEIDON our suspicions that there was too much plasma outside of the first beam grew.

Attempt XIII

With apologies to William Goldsmith, TRITON stooped to conquer. We lowered the fill pressure in the tube to 85μ , the bare minimum necessary for propagation, so that less plasma would be made. We lowered TRITON's current from 60 kA to 20 kA, again the bare minimum, so there would be less of a plasma maker.

And the experiment worked. As shown in Fig. 15, we achieved complete cancellation of the axial current with a longer lived B_z signal. (Compare with the ideal case, Fig. 4.) In some cases we overcooked it and could actually reverse the axial current. Of course, the configuration was not as originally expected: For example, the magnitude of the increase in B_z , over six times that of the initial B_θ , could not be predicted by our two beam model. Also, injecting TRITON at such low current into such a low pressure gas resulted in an axially un-uniform and short lived configuration. Moreover, the current cancellation was complete only within 15 cm of POSEIDON's diode. Even more interesting was the observation in some cases of a complete recovery of the net current within 1 μ sec after POSEIDON's beam passed.

All of these effects were attributable to plasma outside the first beam. To be sure, this was not a particularly dense plasma: the density would have to be less than 10^{14} cm^{-3} (the minimum resolvable by previous Thomson scattering measurements⁵), compared to $6 \times 10^{15} \text{ cm}^{-3}$ in the main channel. Nevertheless, it was dense enough to prevent POSEIDON's beam from propagating, as the beam self-field could not diffuse into the plasma fast enough. The plasma acted like a spring, not only retarding POSEIDON's beam, causing an increase in B_z , but sometimes even collapsing POSEIDON's beam back into the foil after the diode was turned off. Moreover, as mentioned earlier, this plasma partially current neutralized the beam.

Attempt XIV

We verified our suspicions by determining how long we had to wait after TRITON fired before POSEIDON would propagate properly. The answer turned out to be almost 400 μ sec. We knew from previous studies with an HeNe interferometer⁵ that TRITON's plasma persisted for at least 300 μ sec after injection, even though the magnetic fields remained only 20 μ sec.

Attempt XV

Two more attempts followed. The first involved the application of a 1 kG axial field in the drift tube, in hopes to confine the precursor electrons, and hence the resulting plasma, to the flux tube starting at the beam front and ending on the meat tenderizer. The results were the same as without the

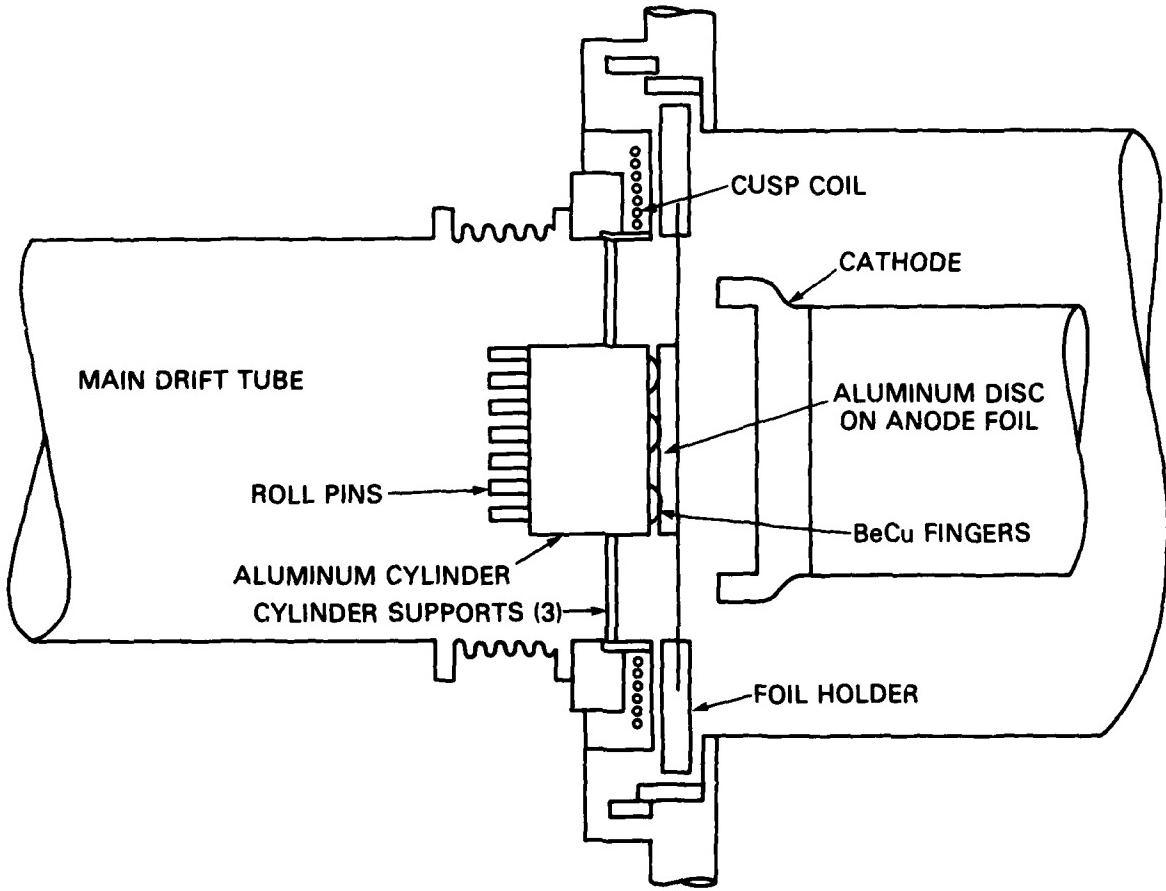


Fig. 14 — The meat tenderizer.

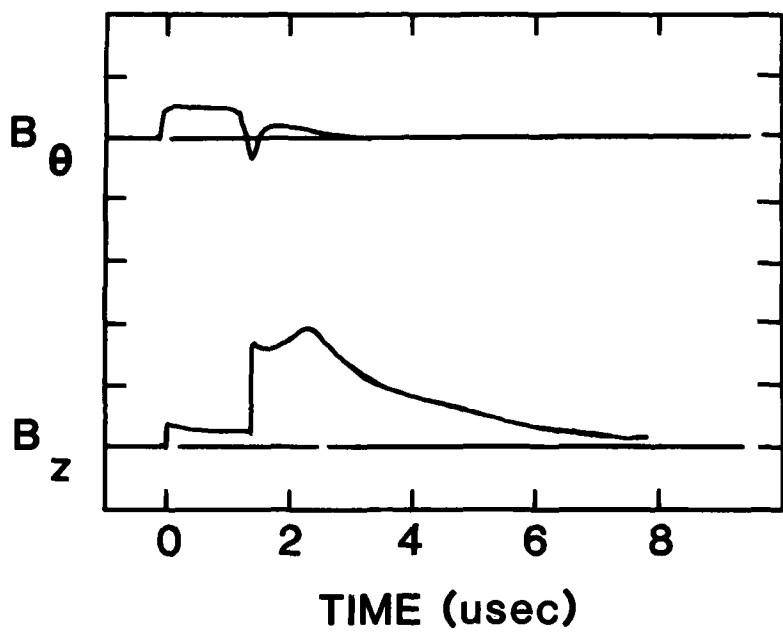


Fig. 15 — Experimental verification of concept. Probes were located 10 cm from POSEIDON diode.

guide field, probably because the field was too weak to effectively radially confine the energetic precursor electrons. (Assuming an energy of 700 kV, their Larmor radius would be 8 cm, which is ample to fill the tube.)

Attempt XVI

The last attempt was to slow down the risetime of POSEIDON so that the beam was injected on a time scale slower than the radial Alfvén time, and thus allow the plasma time to get out of the way of the beam. Of course not knowing the plasma density outside the beam made calculating an Alfvén time difficult, but assuming a maximum density of 10^{14} gave a time of 50 nsec. The best we could do was slow the diode risetime to 80 nsec by inserting a two-turn 500 nH coil in series with the prepulse switch.

No propagation was observed. Blessed with 20/20 hindsight, we immediately realized why ... The characteristics of the beam changed so much over the beam pulse that the beam was never in a regime for equilibrium.

With this realization, we turned out the lights and went home.

IV. CONCLUSION

In conclusion, we were able to prove the scientific validity of using two sequentially injected relativistic electron beams to create a closed field line Compact Toroid. The first beam created a plasma in a reversed-field open-ended configuration, and the second, counterstreaming, beam was used to neutralize the axial current left by the first, and thereby produced the configuration. However, the propagation of the second beam was greatly hindered by plasma external to the first beam channel. This plasma, at least in the present experiments, greatly reduced the parameter range over which the axial current cancellation could be achieved, and thus prevented attainment of a satisfactory plasma confinement system.

V. ACKNOWLEDGMENTS

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Appendix

THE TWO BEAM PROPAGATION MODEL

Current Partitioning

We assume the currents flow as in Fig. A-1, which shows a snapshot in time of the second beam propagating along the tube after the first beam has left the system. Subscripts 1, 2 refer to the first and second beam, respectively. Note that I_2 divides, as shown, with a fraction c returning through the plasma formed by the first beam, and the remainder through the wall. Conservation of toroidal (θ) flux through the loop ABCD yields:

$$(L - x)I_1 \log(1/a_1) + x\{(I_1 + cI_2) \log(a_2/a_1) + [I_1 - (1 - c)I_2](\log(1/a_2)\} = LI_{10} \log(1/a_1), \quad (1)$$

where I_{10} is the value of I_1 just prior to second beam injection. Note that I_1 at a given point can change before the second beam arrives at that point. Defining $A_1 \equiv \log(1/a_1)$ and $A_2 \equiv \log(1/a_2)$, the flux conservation condition, Eq. (1) becomes:

$$I_1 = I_{10} - \frac{x}{L} \left[c - \frac{A_2}{A_1} \right] I_2. \quad (2)$$

Now assuming the branching ratio c will take the value necessary to minimize the toroidal field energy, we can write the energy as:

$$E_\theta = (L - x)I_1^2 A_1 + x[(A_1 - A_2)(I_1 + cI_2)^2 + A_2(I_1 + cI_2 - I_2)^2], \quad (3)$$

and differentiate with respect to c to get:

$$\frac{dE}{dc} = 2 \frac{dI_1}{dc} [LA_1 I_1 + xI_2(A_1 c - A_2)] + 2I_1 I_2 A_1 x + 2I_2^2 A_1 c x - 2A_2 I_2^2 x.$$

Noting that $\frac{dI_1}{dc} = -I_2 \frac{x}{L}$ from Eq. (2), we find that:

$$\frac{dE}{dc} = \left(1 - \frac{x}{L}\right) (A_1 c - A_2),$$

and

$$\frac{d^2E}{dc^2} = A_1 \left(1 - \frac{x}{L}\right) \geq 0.$$

Thus the energy is a minimum if $c = A_2/A_1$, in which case $I_1 = I_{10}$, i.e., the current does not change until the second beam front arrives.

Equilibria

Returning to Fig. A-1, the B 's refer to the fields after the passage of the first beam, β 's refer to those after passage of the second. Subscripts i , m , and o refer to those quantities inside the first beam, between the two beams, and outside the second beam, respectively. From Ampere's law:

$$\beta_{zm} - \beta_{zo} = \frac{-2I_2}{a_2 r_w} \tan \alpha_2. \quad (4)$$

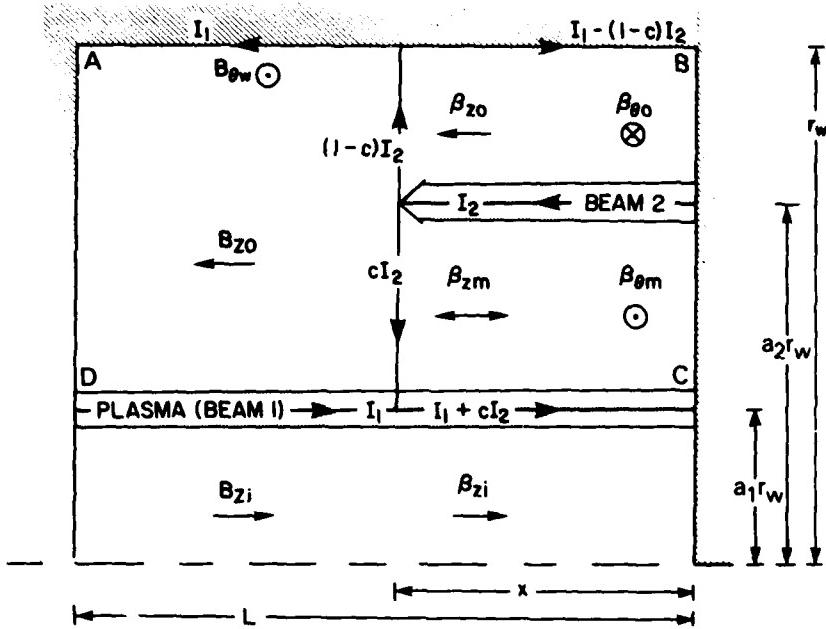


Fig. A-1 — Geometry used for calculating the partitioning of the current and beam equilibria

where α is the beam current pitch angle. Flux conservation for the second beam, in the region between the first beam and the wall yields,

$$(a_2^2 - a_1^2) \beta_{zm} + (1 - a_2^2) \beta_{zo} = (1 - a_1^2) B_{z0}. \quad (5)$$

Previous work with a single beam shows that the axial magnetic flux enclosed by the beam is constant as it traverses the cusp. Thus both:

$$\beta_{zi} a_1^2 = B_{c1} r_{c1}^2, \quad (6a)$$

and

$$\beta_{zm} (a_2^2 - a_1^2) + \beta_{zi} a_1^2 = B_{c2} r_{c2}^2, \quad (6b)$$

where $B_{c1,2}$ is the axial field in the diode and $r_{c1,2}$ is the cathode radius. Thus, from Eqs. (4) and (5) we obtain

$$\beta_{zm} = B_{z0} - \left(\frac{1 - a_2^2}{1 - a_1^2} \right) \frac{2I_2}{a_2 r_w} \tan \alpha_2, \quad (7)$$

and

$$\beta_{zo} = B_{z0} - \left(\frac{a_1^2 - a_2^2}{1 - a_1^2} \right) \frac{2I_2}{a_2 r_w} \tan \alpha_2. \quad (8)$$

Also, from Fig. 1:

$$\beta_{\theta m} = 2(I_1 + cI_2)/a_2 r_w. \quad (9)$$

and

$$\beta_{\theta o} = 2(I_1 + cI_2 - I_2)/a_2 r_w. \quad (10)$$

Considering the plasma of the first beam alone, conservation of flux in the tube yields,

$$B_{zo} (r_w^2 - r_1^2) + B_{zi} r_1^2 = 0;$$

radial force balance gives,

$$B_{zi}^2 = B_{zo}^2 + B_{\theta}^2;$$

and, from Ampere's law,

$$B_{zi} - B_{zo} = \frac{2I_1}{r_w} \tan \alpha_1.$$

These three equations are combined to give:

$$B_{zo} = \frac{2I_1}{r_w} \left(\frac{\tan^2 \alpha_1 - 1}{2} \right)^{1/2} \quad (11)$$

and

$$a_1 = \left(\frac{1 - \cot^2 \alpha_1}{2} \right)^{1/2}. \quad (12)$$

Defining $I_1/I_1 \equiv \zeta$, normalizing all fields to the initial toroidal field at the wall, i.e., $B_{\theta w} = 2I_1/r_w$, and denoting these normalized quantities by $\hat{\cdot}$, Eqs. (7) through (11) become:

$$\hat{\beta}_{zm} = \left(\frac{\tan^2 \alpha_1 - 1}{2} \right)^{1/2} - \zeta \left(\frac{1 - a_2^2}{1 - a_1^2} \right) \frac{\tan \alpha_2}{a_2} \quad (13)$$

$$\hat{\beta}_{zo} = \left(\frac{\tan^2 \alpha_1 - 1}{2} \right)^{1/2} - \zeta \left(\frac{a_1^2 - a_2^2}{1 - a_1^2} \right) \frac{\tan \alpha_2}{a_2} \quad (14)$$

$$\hat{\beta}_{\theta m} = \frac{1 + c\zeta}{a_2} \quad (15)$$

$$\hat{\beta}_{\theta o} = \frac{1 + c\zeta - \zeta}{a_2} \quad (16)$$

$$\hat{B}_{zo} = \left(\frac{\tan^2 \alpha_1 - 1}{2} \right)^{1/2}. \quad (17)$$

In order to generate a compact toroid, a solution in which $\hat{\beta}_{\theta o} = 0$ (no net axial current) and $\hat{\beta}_{zm} = 0$ (no poloidal flux trapped between the beams, i.e., inside the plasma) is sought. Therefore, radial pressure balance requires $\hat{\beta}_{zo} = \hat{\beta}_{\theta m}$, and

$$\left(\frac{\tan^2 \alpha_1 - 1}{2} \right)^{1/2} - \zeta \left(\frac{a_1^2 - a_2^2}{1 - a_1^2} \right) \frac{\tan \alpha_2}{a_2} = \frac{1 + c\zeta}{a_2}. \quad (18)$$

$\hat{\beta}_{zm} = 0$ gives

$$\left(\frac{\tan^2 \alpha_1 - 1}{2} \right)^{1/2} - \zeta \left(\frac{1 - a_2^2}{1 - a_1^2} \right) \frac{\tan \alpha_2}{a_2} = 0, \quad (19)$$

while $\hat{\beta}_{\theta o} = 0$ yields

$$\zeta(1 - c) = 1. \quad (20)$$

Combining these equations leads to $\tan \alpha_2 = 1$, or α_2 , the current pitch angle of the second beam, is 45° . This result is intuitively obvious, since pressure balance requires $\hat{\beta}_{zo}$ and $\hat{\beta}_{\theta m}$, the two orthogonal fields, be equal.

Note that with the requirement that $\hat{\beta}_{zm} = 0$, Eqs. (6) become

$$B_{c2}r_2^2 = \hat{\beta}_{zi}a_1^2 = B_{c1}r_1^2. \quad (21)$$

In other words the axial fluxes enclosed by the two beams at the diodes are equal.

The equilibrium radius of the second beam, α_2 , and the value of ζ , can be found by setting $\alpha_2 = 45^\circ$ in Eq. (19), e.g.

$$a_2 \left(\frac{\tan^2 \alpha_1 - 1}{2} \right)^{1/2} = \zeta \left(\frac{1 - a_2^2}{1 - a_1^2} \right), \quad (22)$$

and solving it numerically with eq. (20)

$$\zeta = 1/(1 - c) = \log(a_1/a_2)/\log(a_1), \quad (23)$$

where a_1 is determined from Eq. (12).

The inductance of the second beam can be calculated in order to determine the energy necessary to close the current lines. The magnetic energy per unit length, before the second beam arrives, can be written as:

$$E_1 = \pi r_w^2 (1 - a_1^2) \frac{B_{zo}^2}{8\pi} + \int_{a_1 r_w}^{r_w} \left(\frac{2I_1}{r} \right)^2 \frac{1}{8\pi} 2\pi r dr,$$

or

$$\frac{r_w^2 B_{zo}^2}{8} (1 - a_1^2) + I_1^2 \log(1/a_1). \quad (24)$$

The magnetic energy per unit length, after the second beam has passed, is, similarly,

$$E_2 = \frac{r_w^2 \beta_{zo}^2}{8} (1 - a_2^2) + I_2^2 \log (a_2/a_1). \quad (25)$$

Thus, the inductance, L_2 , of the second beam can be defined as

$$\begin{aligned} L_2 &= \frac{2(E_2 - E_1)}{I_2^2} \\ &= \frac{1}{\zeta^2} \{ \hat{\beta}_{zo}^2 (1 - a_2^2) - \hat{B}_{zo}^2 (1 - a_1^2) - 2 \log (1/a_1) \} \\ &\quad + 2 \log (a_2/a_1), \end{aligned} \quad (26)$$

where all the quantities on the right hand side can be determined from the beam pitch angle.

The ratio of the energy required of the second beam to that required of the first can be calculated from,

$$\frac{E_2}{E_1} = \frac{L_2 I_2^2}{L_1 I_1^2} = \zeta^2 L_2 / L_1, \quad (27)$$

where L_1 , from the single beam model, (Ref. 3, Eq. (14)) is given by

$$L_1 = (1 - a_1^2) \tan^2 \alpha_1 + 2 \log (1/a_1). \quad (28)$$

In Fig. A-2 are plotted r_2/r_w , r_1/r_w , obtained from Eqs. (21) and (22), and Eq. (12) respectively, and I_2/I_1 and E_2/E_1 , obtained from Eqs. (22) and (27) respectively, all as a function of the first beam current pitch angle. The vertical dashed line in the upper drawing indicates the pitch angle above which axial contraction of the plasma is expected because it is energetically favorable.

From Fig. A-2 one can see that a pitch angle of $\alpha_1 = 55^\circ$ is optimal, because (1) axial contraction is expected, (2) the beam radii are sufficiently different to prevent interference of the second beam by the plasma of the first, (3) the second beam is well away from the wall, (4) only a modest cusp field is required to achieve these pitch angles (see Fig. 2, Ref 3), and (5) only a modest I_2/I_1 required.

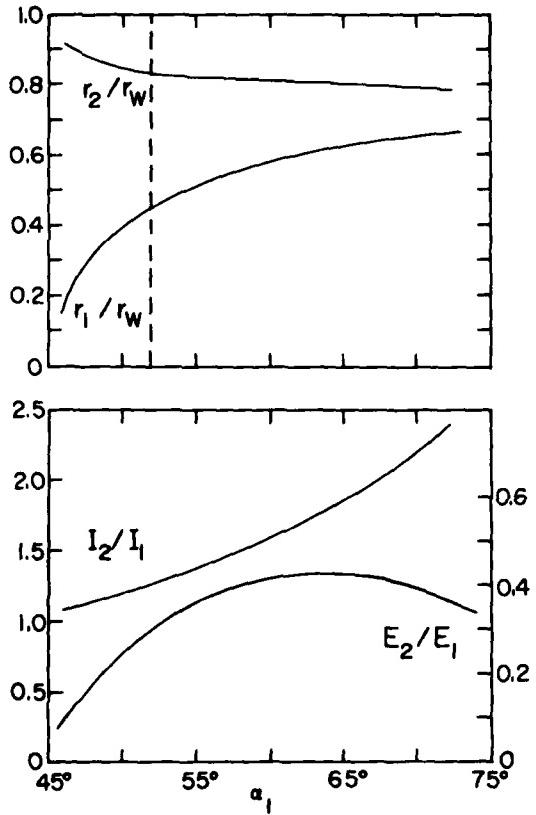


Fig. A-2 — r_2/r_w , r_1/r_w , I_2/I_1 and E_2/E_1 as a function of α_1

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